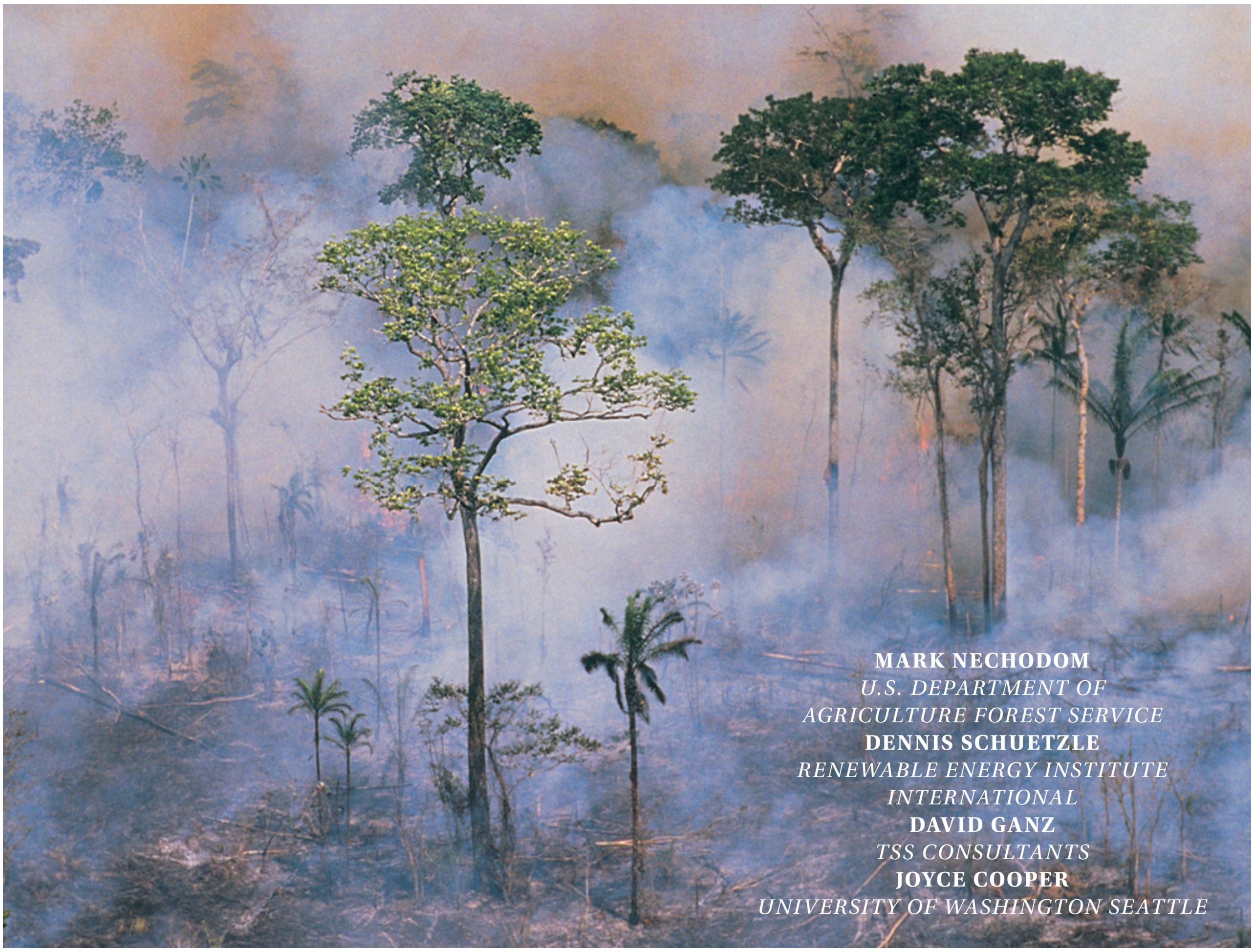
Sustainable Forests, Renewable Energy, *and* *the* ENVIRONMENT



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Life-cycle assessment tools can help scientists quantify potential environmental risks and benefits of forest remediation and determine whether waste biomass can be converted to renewable energy economically.

Forests, rangelands, and grasslands play an important role in sustaining the earth's global environment. Wildland fires of high intensity have adverse effects on local, regional, and global environments. Several major studies are under way to determine how forests and wildlands can be remediated to improve their health, reduce climate change impacts, and contribute to renewable-energy goals.

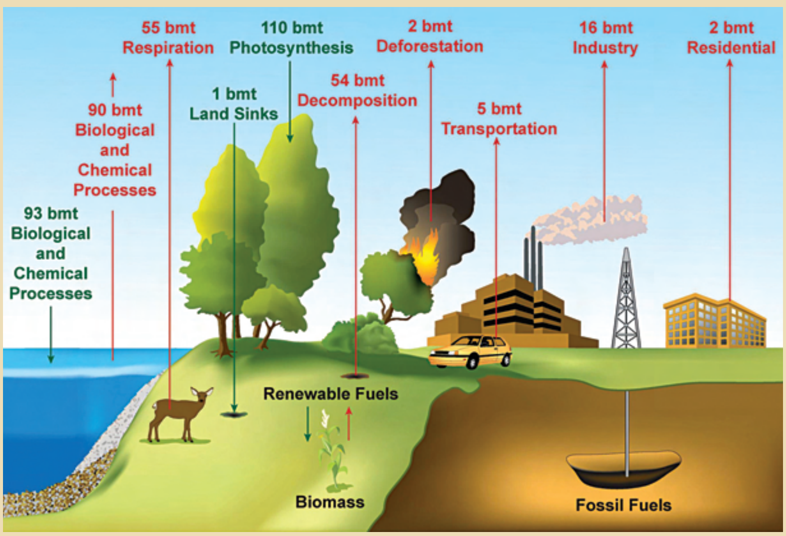
This article provides an overview of the Biomass to Energy project, a California study that explores the economic, environmental, and energy trade-offs of forest remediation strategies designed to reduce the occurrence and severity of wildfires. The study uses life-cycle assessment (LCA) tools to quantify the potential environmental risks and benefits associated with forest remediation and to determine whether the waste biomass generated from forest remediation processes can be economically converted to renewable electricity and fuels with a resulting positive benefit to the environment.

Preliminary modeling results suggest that thermochemical conversion of biomass to ethanol is the most economically efficient process. However, the unsubsidized costs of collection, processing, and transportation of feedstocks continue to challenge the economic viability of the entire forest-to-energy approach. This article presents improvements in system-analysis methodologies as well as preliminary modeling results from the Biomass to Energy project. Recommendations are provided for further environmental, economic, and ecological research that will be needed to better quantify the complex relationships among forest sustainability, renewable energy, and the environment.

FIGURE 1

Major sources and sinks of atmospheric CO_2

All values are given in bmt/yr. Data from Renewable Energy Institute International.



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Forests and the environment

Forests, as well as rangelands and grasslands, play an important role in the earth's natural global CO_2 and climate balance, and they affect the sustainability of flora, fauna, water, air, soil resources, and ultimately human welfare. The effects of wildlands on the equilibrium concentration of CO_2 in the atmosphere are a major focus of current scientific and public-policy research (*1*). Figure 1 summarizes the primary global sources and sinks of CO_2 as reported in current studies (*2–4*).

Wildlands are estimated to absorb and fix an estimated 110 billion metric tons per year (bmt/yr) of CO_2 via photosynthesis. In addition, 93 bmt/yr of CO_2 is sequestered by biological and chemical processes in the oceans and surface waters, and ~1 bmt/yr is sequestered by inorganic chemical processes at the earth's surface. The total sinks of CO_2 are estimated to be 204 bmt/yr.

This absorptive effect on atmospheric carbon can be compared with CO_2 sources, which include the decomposition of biomass (~54 bmt/yr of CO_2 globally), respiration from animals (55 bmt/yr of CO_2, of which humans contribute 2.8 bmt/yr), and the burning of fossil fuels (~23 bmt/yr). The total amount of CO_2 from all sources is 224 bmt/yr.

Because global sources of CO_2 are currently 20 bmt/yr greater than global CO_2 sinks, the concentration of atmospheric CO_2 will continue to increase. However, the potential influence of wildlands on the sources and sinks of global CO_2 is only part of the total picture.

According to the World Resources Institute, >50% of the earth's natural forests have been destroyed already (*5*). Studies have shown that the clearing and burning of rain forests in West African countries, such as Nigeria, Ghana, and Ivory Coast, may have contributed substantially to nearly two decades of droughts in the interior of Africa, with accompanying hardship and famine. Clearing and burning of forests are estimated to emit 2 bmt/yr of CO_2 to the atmosphere. At current rates of deforestation, Woodwell and colleagues (*6*) estimate that a 95% loss of historic forest cover would result in 9 bmt/yr of CO_2 emitted to the atmosphere.

During the past several decades in the U.S., a generally warmer climate, combined with public-policy and land-management practices designed to protect forests (e.g., fire suppression and policies restricting thinning or excessive harvesting), has led to increasingly dense vegetation. These conditions have resulted in increased incidence and intensity of wildfires beyond what is considered healthy for fire-adapted wildlands. The map in Figure 2 shows "condition classes" where red (condition class 3) represents the greatest "departure from the natural regime" (*7*), and therefore the highest risk of fire.

Management of wildland resources can have a significant impact on regional water fluxes and the global accumulation of CO_2. Regional wildland management efforts rely on the combined efforts of many public and private stakeholders to create sustainable natural and built systems.

Wildland fires

Despite substantial infrastructure and budgets dedicated to fire suppression in the U.S., the annual area burned by wildfire has increased in the past decade. Wildfires burned a record 9.7 million acres of U.S. forests and wildlands in 2006, compared with an annual average of 6.6 million acres during 1999–2006. The upward trend is due in part to forests that are heavily overstocked with small-diameter trees and brush, substantially increasing the risks of catastrophic wildfires (*8*).

In 2003, 13 large wildfires in Southern California burned >750,000 acres of forest and brushland, destroyed >4500 structures, displaced ~100,000 people, and conservatively cost the state and federal governments $1.2 billion in total expenditures. It was the deadliest and most devastating series of fire events in more than a decade, prompting evacuations and public advisories about excessive levels of particulate matter (PM), carbon monoxide, volatile organic compounds, and ozone. Phuleria et al. (*9*) found that PM_{10} levels increased by a factor of 3–4 in the Los Angeles air basin, resulting in a higher incidence of asthma and other respiratory ailments. The October 2007 fires in Southern California were even more devastating, displacing >500,000 residents, destroying >3200 structures, and burning >500,000 acres. Early estimates of atmospheric pollutants vary widely, but because of the vegetation involved, they clearly exceed those of the 2003 wildfires.

When wildfires occur in heavily overstocked forests, they often become larger and more severe, moving from brush and smaller trees ("ladder fuels") up into the crowns of larger trees. Crown fires are usually more severe, produce more emissions, and damage forests more than lower intensity fires. The mechanical removal of small trees and understory biomass reduces the risks of catastrophic wildfires.

The Biomass to Energy project

In 2003, the California Energy Commission initiated a collaborative project with the U.S. Department of Agriculture (USDA) Forest Service; the California Department of Forestry and Fire Protection; and several other agencies, universities, and consulting firms (see Table S1 in the Supporting Information) to evaluate the potential net benefits associated with the removal of forest biomass to reduce the threat of wildfires and to identify the most effective use of waste wood products.

A major objective of this effort was to compare the capability of current and next-generation technologies for the conversion of waste wood from forest remediation efforts to renewable-energy products. A "4E" assessment approach, drawn from a methodology developed by Kreucher, Han, and Schuetzle (*10*), was used to evaluate biomass conversion processes with respect to their technology effectiveness (E1) (e.g., reliability, safety, and product yields), energy efficiency (E2), potential environmental impact (E3), and economic viability (E4).

Five technologies were evaluated, ranging from a standard wood-fired, electric power plant to an advanced thermochemical conversion process for the coproduction of bioalcohol and electricity. The project's analyses (see Tables S2 and S3 in the Supporting Information) were based on plants that process 500 dry tons (DT) per day of forest biomass within a 30–40 mi radius of forest remediation activities at a cost of \$45/DT of waste wood delivered to a plant site (*11*).

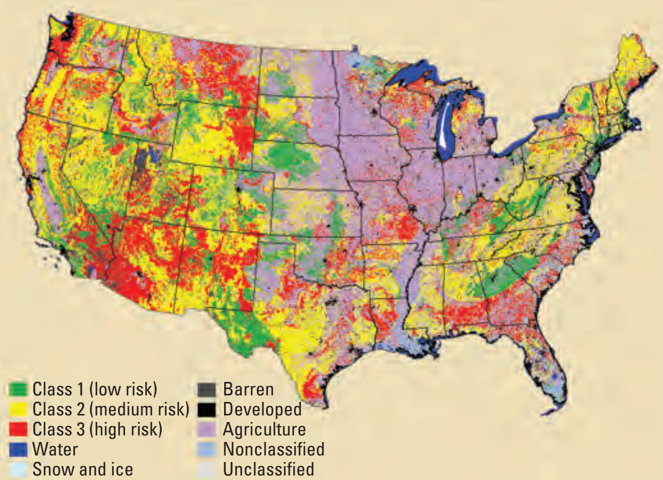
If only the costs of energy production are considered (as opposed to full life-cycle costs), thermochemical conversion processes currently have the potential to coproduce ethanol and electricity at a price with a return on investment of >30%, not including financial and tax incentives. Such thermochemical processes are used to convert forest biomass into a biogas, called syngas. Syngas can be coconverted to ethanol or other fuels (e.g., diesel) by using catalysts and to electricity by using reciprocating engines. Conversion technology studies, conducted as part of the Biomass to Energy project, indicate that 1 DT of forest waste can be coconverted to 75–85 gal of bioethanol fuel and 500–600 kWh of electricity. These yields represent an average net energy conversion efficiency of 50%.

If only one-third of the estimated 368 million DT of forest waste available in the U.S. every year (*12*) were converted to energy with these technologies, 9.2–10.4 billion gal of ethanol and 61–74 billion kWh of electricity potentially could be produced (*13*).

FIGURE 2

Potential risk of wildland fires in the U.S.

Adapted from LANDFIRE Rapid Assessment fire regime condition classes.



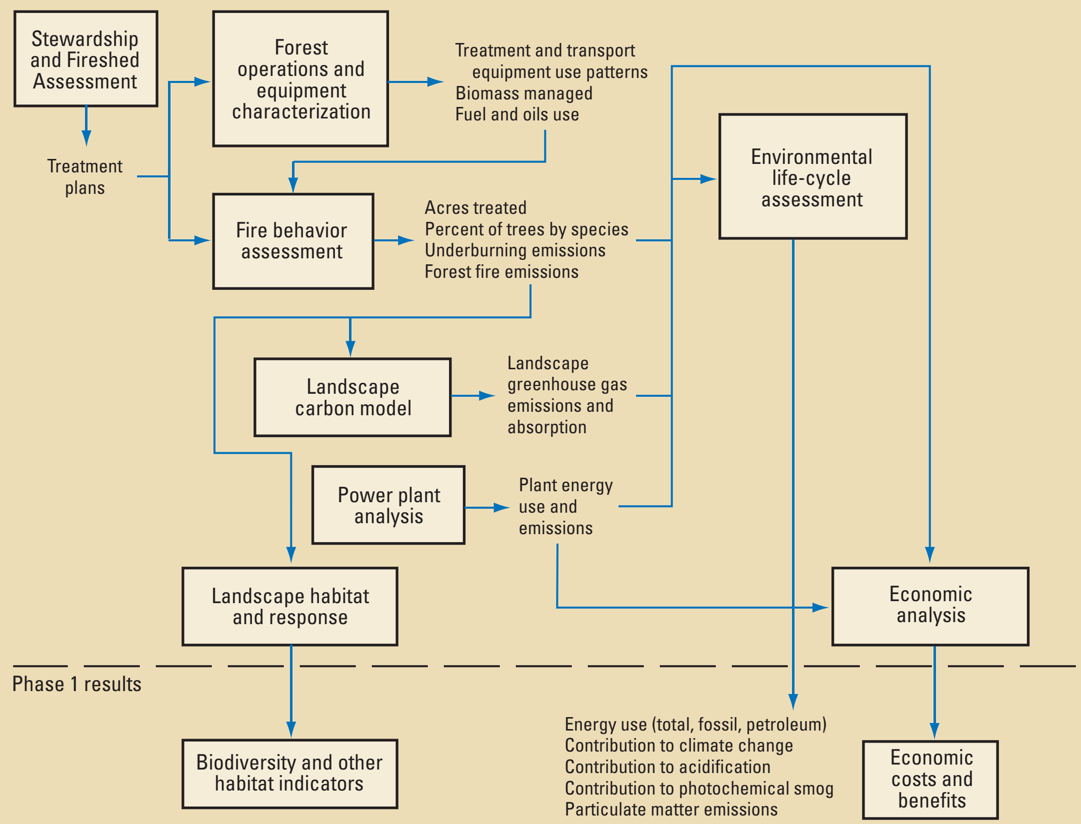
Life-cycle assessment

The cost competitiveness of these and other technologies can be increased substantially by calculating the full environmental benefits and life-cycle costs of energy production. By expanding the boundaries of the analysis from the conversion technology to the system life cycle, the project demonstrates how environmental trade-offs and benefits may be counted more comprehensively to appreciate the full impacts of linking renewable bioenergy production to forest remediation (*14*).

The Biomass to Energy LCA is organized around the LCA protocol standardized by the International Organization for Standardization (*15–17*). The first phase, goal and scope definition, describes the reasons for carrying out the study, the intended audience, geographic and temporal considerations, the system function and boundaries, data categories, comparative (or reference) systems, impact assessment and interpretation methods, and plans for critical review. Next, in the inventory model, the life cycle is subdivided into a set of unit processes, each encompassing the activities of a single operation or a group of operations. The inventory model quantifies material and energy use and waste by each unit process. These are then linked to one another by economic flows (flows within the economic system, such as the production of biomass or the use of fuel or steel) and environmen-

FIGURE 3

Biomass to Energy LCA model boundary and structure



tal flows (flows out of and into the environment, such as the consumption of energy, land, or iron ore, or CO_2 emissions). Third, the impact assessment estimates the contribution of environmental flows to environmental benefits (e.g., habitat protection) and impacts (e.g., global warming). Finally, the interpretation step identifies sensitive parameters and quantifies uncertainties in results.

The Biomass to Energy project integrates existing USDA Forest Service models of fire planning and forest ecology with LCA models of energy use, emissions, and cost. The LCA portion of the project assesses the environmental impacts associated with options for treating, disposing of, and using forest biomass, and producing electricity or biofuels. Figure 3 illustrates the boundaries of the formal LCA and its integration with the other submodeling processes, including wildfire, wildlife habitat, carbon flux, and economics.

To ground the analysis in real-world experiences and data sources, the concept of a landscape archetype was developed. This landscape archetype is an area large enough to represent landscape-level risks of high-intensity wildland fires (e.g., a large river basin or several watersheds). The qualifying landscape must also encompass a broad range of ownerships, wildlife habitats, and infrastructures. The project identified a 2.7 million acre pilot landscape located in the northern Sierra Nevada range in California, including portions of Lassen, Plumas, Sierra, Shasta, and Tehama counties. Land ownerships are grouped into five categories by land management capabilities: public multiple use (50% of land area), public conservation and recreation (15%), industrial private forests (17%), nonindustrial private forests (14%), and urban core (4%).

Forest remediation is focused on removing small trees, branches, brush, and litter, with different prescriptions for public multiple use (PMU) and industrial private forest (IPF) lands. The PMU treatments are assumed to be carried out during a 40 yr period at 10 yr cycles with an average of 17 DT/acre of biomass removed. From the IPF lands, which have different management objectives, an average of 20 DT/acre of forest biomass is removed after saw timber is harvested. Total biomass loading on the pilot landscape ranges from ~4 DT/acre for grasslands to 60–80 DT/acre for fully stocked forests.

The model assumes that if this landscape is left untreated, an average of 66,400 acres would burn per decade. The landscape also is assumed to have a series of large- and medium-sized fires (10,000 and 5000 acres, respectively). Fire and vegetation interactions are modeled by the USDA Forest Service's Stewardship and Fireshed Assessment process (*18*), and wildlife habitat responses are modeled with California Wildlife Habitat Relations and Multi-Species Inventory and Management analysis tools. An atmospheric carbon flux submodel, which calculates the amount of carbon volatilized by wildfire, prescribed burning, and decomposition, has been developed. It further compares the treated and untreated landscape and finds, in every treatment scenario, that net stored carbon, combined with the savings associated with fossil-fuel offsets, provides a positive carbon benefit during the 40 yr modeling cycle.

After treatments are modeled, the same fires are "burned" for four decades, and the model looks for changes in costs and benefits because of treatments. The total biomass available for conversion is calculated by measuring the amount of vegetation that would be removed during a treatment. The next modeling steps include processing, transportation (assuming an average haul distance of 30 mi), and energy production.

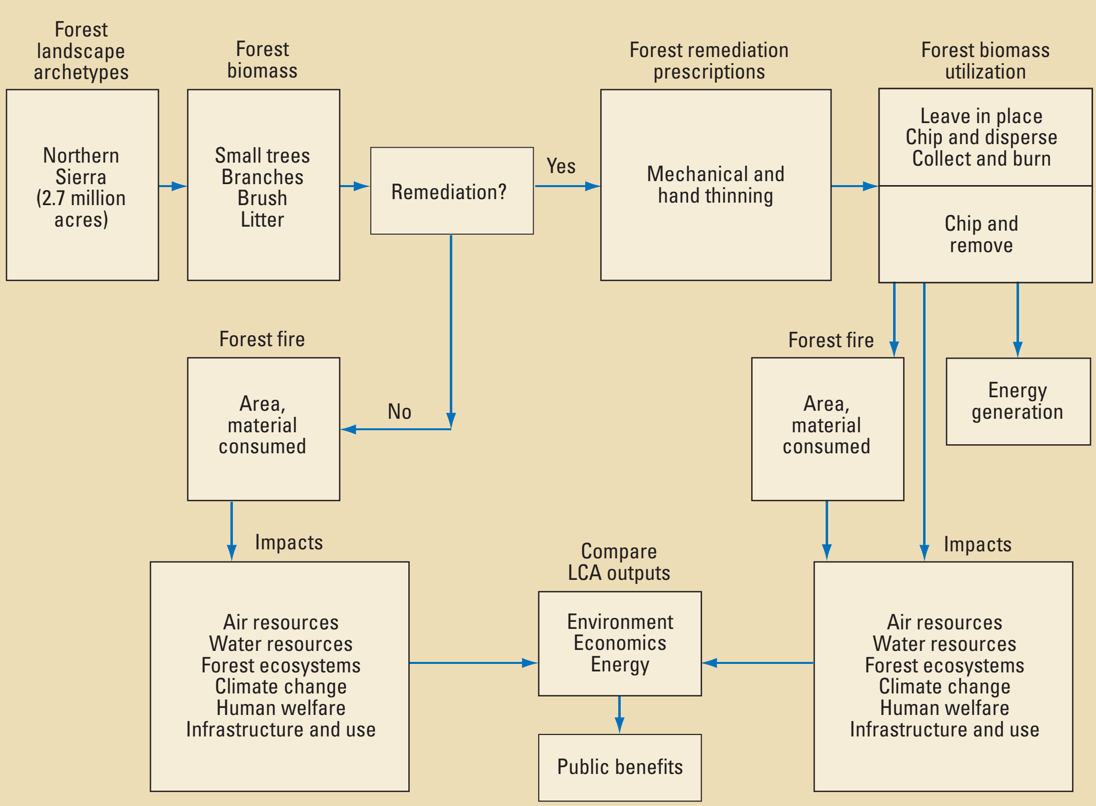
The LCA conversion technology submodel compares costs and efficiencies among five energy-conversion technologies while simultaneously allowing comparison with power generated from natural gas. Figure 4 illustrates the energy, material, and environmental accounting flows in the Biomass to Energy LCA model.

The LCA model also supports a more comprehensive life-cycle cost assessment (LCCA), which can include an economic analysis to normalize and compare impacts. The LCCA is built around the same unit processes as the LCA model, with the recognition that although it is difficult to place a price on environmental quality, the equivalent is being done all the time. Policy makers very often must make trade-offs among public benefits and set the rules by which costs and benefits are distributed. The optimal level of forest remediation or fuel treatment requires an analysis of the trade-offs between the costs and benefits of treatment. Historically, this type of analysis has not effectively quantified and accounted for the social and environmental benefits derived from fire mitigation treatments. To date, biomass power has successfully garnered subsidies in California and elsewhere because of the offsets it provides to air quality and other environmental impacts. Those subsidies have been relatively small, and they are often not sustained during downturns in public revenues. Many policy makers are interested in market-based mechanisms in which maximum environmental benefits can be pursued with minimum direct public subsidy. The key component often lacking is a credible method to establish relative values.

Several key public-policy questions need to be resolved to structure financial incentives that correspond to avoided costs. The U.S. EPA's sulfur oxides (SO_x) trading system is an example in which producers were required to purchase reductions elsewhere to continue emitting SO_x. This program significantly reduced the total load of SO_x in the atmosphere (*19*). Other studies have shown the public benefits derived from the generation of electricity from biomass waste. Morris (*20*) estimated that the economic benefits of using waste biomass feedstocks for the

FIGURE 4

Biomass to Energy LCA accounting flows



generation of power averaged 11.4 ¢/kWh. Most of the economic benefits from this study were associated with the reduction in criteria air pollutants only. Many other possible environmental and social benefits were not considered in the Morris estimate, such as improved watershed and wildlife values.

Ultimately, the combination of LCA and LCCA models can be used to explore opportunities for converting forest biomass to electricity or liquid fuels on the basis of economic viability, environmental impacts, and energy efficiency. These models also will allow policy makers to evaluate the effectiveness of alternative forest biomass management policies to meet public goals, stakeholder needs, and government regulations.

Future perspectives

A significant proportion of wildland biomass may have the potential to produce renewable fuels and energy. The conversion of forest biomass to useful energy becomes a critical economic and environmental tool, assuming that collection, processing, and transportation are economically viable. The Biomass to Energy project is helping to provide scientists with information about potential economic, energy, and environmental trade-offs associated with various options for managing forest biomass. Future models will explore the impacts of more aggressive management strategies and whether they might be designed for maximum fire protection or for maximum carbon storage benefits. The ultimate purpose of the project is to allow the public and decision makers to experiment with complex, landscape-level outcomes and to understand the less obvious trade-offs and consequences of policy decisions.

As an increasing number of states pass laws that require renewable-energy procurement standards and greenhouse gas reduction measures, forests, wildfire, and biomass energy may make significant contributions to finding solutions. The results, findings, and conclusions of this project and other similar studies will help establish policies, legislation, incentives, and funding initiatives related to climate change and renewable energy.

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Supporting Information

Supporting Information is available online that presents the methods used to calculate production rates, costs, and environmental impacts of the five biomass conversion technologies described in the main article. A compilation of research needs for LCA model improvement also is provided, along with a list of project contributors.

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